

Commercial-Off-The-Shelf (COTS) Indirect Energy Conversion Isotope (IDEC) Design Structure and Power Management

by Johnny Russo, Dr Marc S Litz, and Dr Dimos Katsis

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14. ABSTRACT <p>Long-lived power sources are of great interest to the US Army for use in unattended sensors and communication nodes operating in remote locations. A tritium (^3H)-based isotope source, ^3H-encapsulated in zinc selenide (ZnS) phosphor, has been designed using indirect power conversion (nuclear \rightarrow radioluminescence \rightarrow photovoltaic [PV] effect). ^3H is an abundant, low-energy, beta-emitting isotope. The expected electrical power generated from this power source is 100 μW_e, fabricated from commercial-off-the-shelf (COTS) materials. The power source is designed to be durable using function graded/layered materials (FGM) packaging for device survivability and leakage prevention. The power sources are designed into 20Ci cassettes consisting of 4 sandwiches (PV-^3H-PV). The entire battery's dimensions and footprint are similar to a BA5590 US Army battery. The packets and components of the battery have self-locating features, which, in turn, make the battery easier to assembly. The internal assembly and structure replicate a typical lithium battery design. The overall design, material selection, and components of the battery offering long-lived power attributes are described. This capability is expected to benefit the Army's low-power sensor requirements.</p>					
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1. Motivation

The objective of this project is to develop a multiple-decade battery using only commercially available components. The benefits of this type of designing will enable a new long-lived power source that is inexpensive compared to using expensive special-purpose materials and components. The battery will be simple to use (by virtue of its common form-fit and function), low cost (by virtue of its commercial-off-the-shelf [COTS] design), and long lived (by virtue of the 12.6 year half-life of tritium [^3H]), and thus will serve the Army's needs for long-lived, low-power applications.

2. Background

There is a great need for energy sources that can power unattended sensors for more than a decade without adding new logistics tails. Unattended sensors can be located in the most harsh and remote locations, which are often dangerous for personnel maintenance and power source replacement. The power source must last the lifetime of the sensor. Unlike chemical batteries, the higher energy densities of radioisotopes allow the sensors to operate for infrastructure lifetimes (~ 150 years). Sensors can provide environmental sensing (electromagnetic [EM], vibration, acoustic, temperature, and radiation) information for decades in urban and remote locations without maintenance or power source replacement. Isotope batteries (iBATs) have the potential to become reliable, robust, and maintenance-free power sources for remote, long-term, low-power sensors. iBATs are different from chemical batteries because they are self-contained energy sources using radioisotope decay. The minimum power needed to fully accomplish a wide range of duties would be $100\text{ }\mu\text{W}_e$ consistently for at least 10 years (described further in section 6). The power source would trickle charge low-power sensors, having an open circuit voltage of 3.3 V or greater (typical lithium battery V_{oc}). iBATs introduce new operational capabilities because of higher energy density, thermal robustness, and a vastly longer lifetime compared with commercially available chemical batteries.

Indirect power conversion is used for the COTS iBAT. The conversion process is based on a 2-step process converting nuclear decay to optical energy, then optical to electrical energy. The isotope is encapsulated inside a phosphor. The beta decay excites the phosphor generating photon emission, usually at a narrow frequency bandwidth (radioluminescence). Photovoltaics (PVs) surrounding the phosphor platelets convert the optical energy into usable direct current (DC) electrical energy. There are inefficiencies inherent in the 2-step conversion processes. Figure 1 shows the 2-step energy conversion efficiencies.

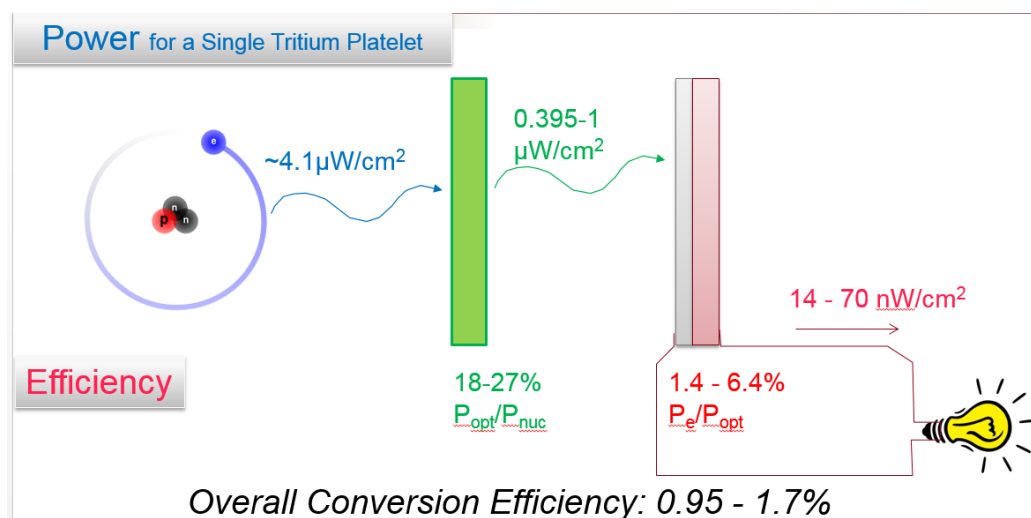


Fig. 1 Two-step conversion efficiency in an IDEC COTS iBAT¹

The intensity of the radioluminescence is determined by the beta decay energy spectrum and phosphor chemical composition. The highest reported radioluminescence efficiency is 18–27% using zinc selenide (ZnS), which generates a $(2.375 \pm 0.475 \text{ eV})$ photon with a luminosity of $528 \pm 40 \text{ nm}$ at $1 \mu\text{W}_{\text{opt}}/\text{cm}^2$.^{1,2} Overall, the advantages are it uses an enhanced power source lifetime semiconductor degradation from direct isotope radiation exposure, uses commercially available components and US Army materiel, and is easily licensable and deployable.

Three power management parameters of interest are initial energy capacity, self-discharge, and chemical degradation rate. Isotope-based power sources excel at these characteristics. The use of indirect energy conversion prevents degradation to the components used in the outer packaging, phosphor, and PV converter. The present state of the art in battery technologies are centered on various formulations of lithium. These formulations balance energy density with cell lifetime and typically deliver the longest lifetime for cells that have very low power density. In the best-case cells, lithium thionyl chloride (LiSoCl_2), the operating energy starts off comparably well compared with ^3H , but a steep drop-off occurs near the end of life for both the chemicals and electrodes in the battery. Figure 2 shows energy availability versus years for typical chemical batteries and the ^3H iBAT.

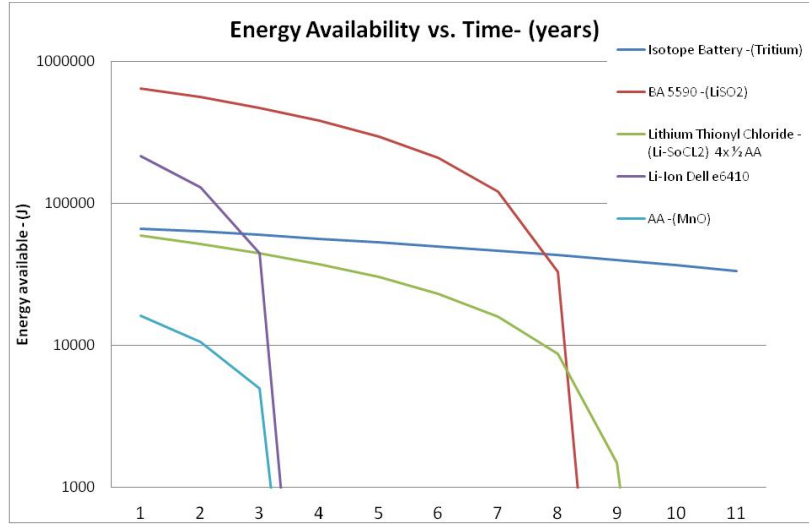


Fig. 2 Energy drop-off due to chemical degradation in batteries shown as a function of time¹

The most difficult part of the design was selecting a solar cell that is sufficiently efficient when exposed to narrowband wavelengths and low light conditions. By bandgap matching the PV to the optical phosphor output and identifying fabrication process effects on PV efficiency, the total device efficiency could be optimized. Silicon (Si) solar cells such as amorphous Si (a-Si or a:Si) are the most available and inexpensive in the market with a 1.1 eV bandgap (E_g). Gallium arsenide (GaAs) thin-film solar cells have a larger bandgap of 1.4 eV. Indium gallium phosphide (InGaP) has the largest bandgap of 1.9 eV. GaAs and InGaP have a narrower quantum efficiency compared to Si.¹ InGaP's bandgap in relation to the phosphor wavelength reduces losses from thermalized photons. After evaluating these 3 samples along with other types, the highest conversion efficiency and specific power density was found in the InGaP.¹ The PV efficiency drastically reduces the required activity of radioactivity in the system. Theoretical predictions and experimental results from PV samples have shown that an InGaP-based iBAT can produce 100 μW_e from 100 Ci, which was the design goal.

The 528 nm (2.2 eV) photon emitted from the ZnS phosphor is sufficiently energetic to raise the valence band to the conduction band for Si (1.1 eV), GaAs (1.4 eV), and InGaP (1.9 eV). Because the band gap of InGaP is higher than that for Si, it is better matched and thus less energy (thermalization loss) is wasted when matching the InGaP bandgap (1.9 eV) to the photon energy of 2.2 eV. Figures 3 and 4 show plots of wavelength vs. bandgap and radioactivity vs. PV efficiency.

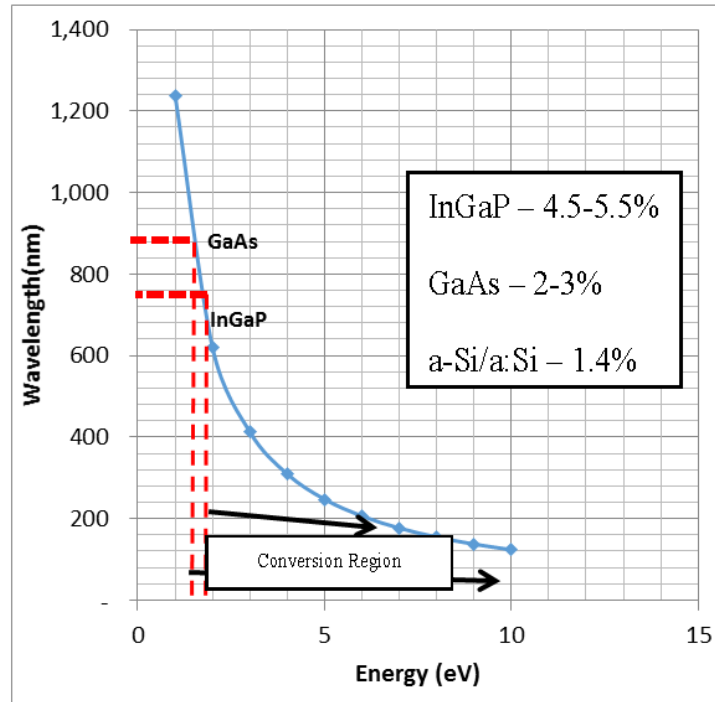


Fig. 3 Wavelength vs. PV type bandgap¹

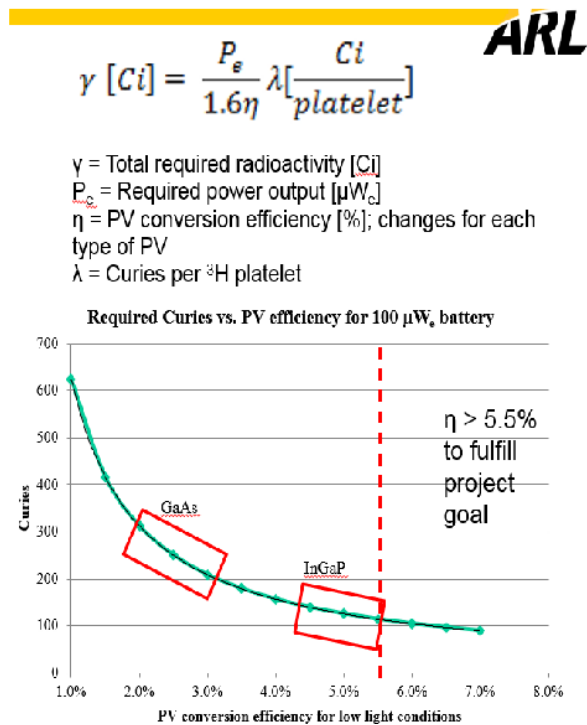


Fig. 4 Isotope activity vs. PV efficiency

3. Components and Mechanical Design

3.1 List of Components

The following is a list of the components used:

1. Alta Devices GaAs thin-film/Microlink InGaP solar cells
2. $^3\text{H}/\text{ZnS}$ phosphor platelets
3. ABS cassette and enclosure case
4. Board-to-board electrical connectors
5. Cymbet EnerChip thin-film battery

3.2 Photovoltaic Solar Cells

Purpose: The PV cells used in this system convert 528 ± 40 nm photons with a luminosity of $1 \mu\text{W}_{\text{opt}}/\text{cm}^2$ to usable electrical energy, which trickle charges onboard backup batteries.

Features: The Alta Devices PV solar cell is a GaAs single junction thin, flexible, and lightweight solar cell. The dimensions are 5 by 2 cm (length x width) with a thickness of 0.110 mm and weight of 180 mg. The quoted electrical characteristics are under 1 Sun ($1000 \text{ W}_{\text{opt}}/\text{m}^2$) light conditions. The energy conversion efficiency is 24.2% with maximum power output of 220 mW.³ The open circuit voltage is 1.09 V; the short circuit current is 239 mA. Finally, the fill factor (FF) is 84.2% under full sun conditions.³ Five cells are connected in series. Fifty platelets are attached to the PV surface (5 Ci). Figure 5 shows illustrations and pictures of Alta cells and ^3H platelet dimensions.

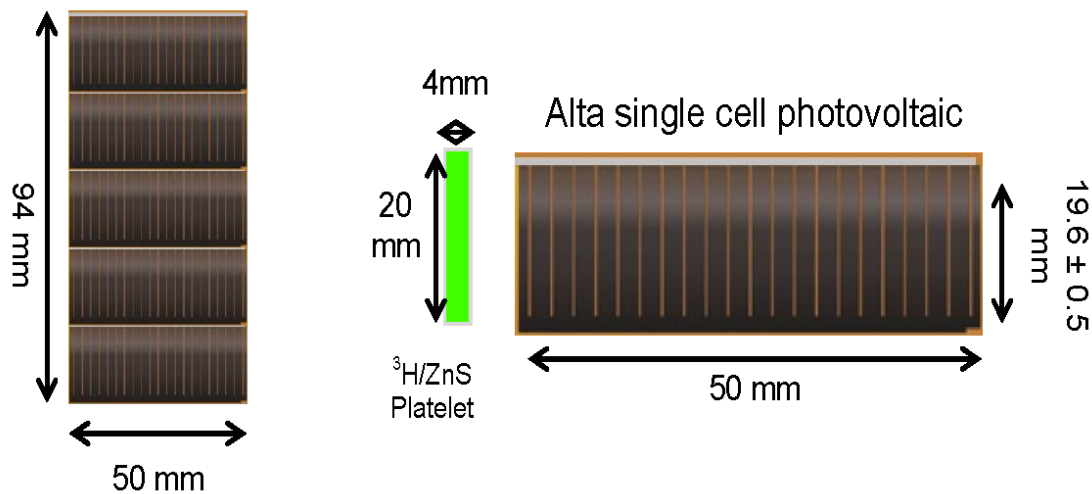


Fig. 5 Illustrations of the Alta solar cells dimensions and the solar cell array in series³

The other solar cell type is a Microlink PV. The solar cell material is InGaP, which is 2 times more efficient than GaAs (at 528 ± 40 nm and $1 \mu\text{W}_{\text{opt}}/\text{cm}^2$). It is neither flexible nor lightweight. The thickness is approximately 1 mm. The solar cell length and width dimensions can be easily altered or optimized depending on the wafer type or application purpose. The preferred dimensions for the COTS iBAT would be approximately 5 by 5 cm. There would be 5 Ci on each layer and no platelet overhang, which is visible in GaAs arrangement. Both PV arrangements do not need a printed circuit board, reducing the overall thickness of the COTS iBAT. Figure 6 shows an image of an InGaP solar cell.

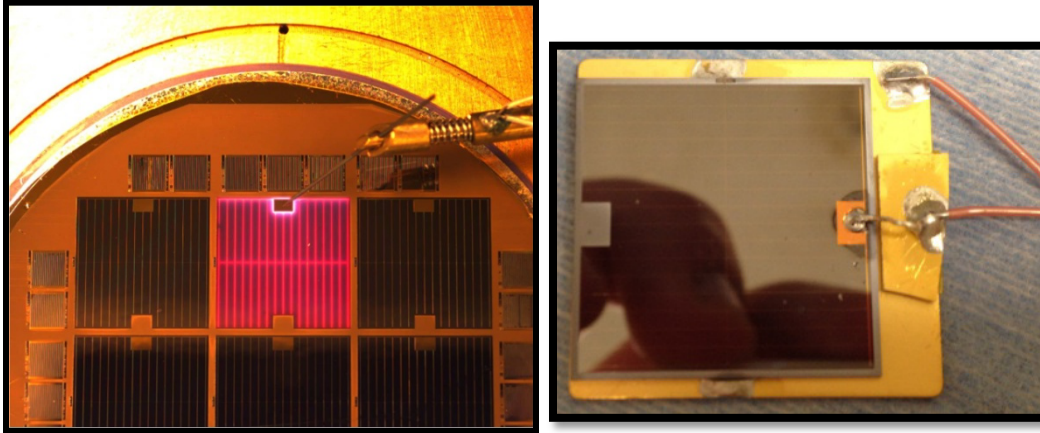


Fig. 6 Image of the Microlink InGaP solar cell used for testing (2x2 cm) and the wafer

3.3 Cassette

Purpose: The cassette is the case for the 4 sandwiches. This adds additional mechanical support for the vital components. The shape and features of the cassette allow the user to individually slide the cases into the enclosure. They are designed to consistently orient themselves when slid into the larger enclosure (guide surfaces).¹¹

Material: The material is ABS plastic formed via injection molding or additive manufacturing.

Features: The front section of the case has an oval shape to allow 2 to 4 screws to secure the case's cover in place. This oval section rounds off to a rectangular and narrower shape. There are 2 fins on each side of the case. The user slides the cassette into the enclosure by lining the fins in-between single fins on the enclosure's side walls. This step is repeated for the other quads that are stacked on top of each other. The case's cover has 2 screw clearance holes on both sides. The four 0-80 screws secure the case cover to the cassette. There is cut-out hole for the Samtec board-to-board electrical connector. Figure 7 shows illustrations of the cassette.

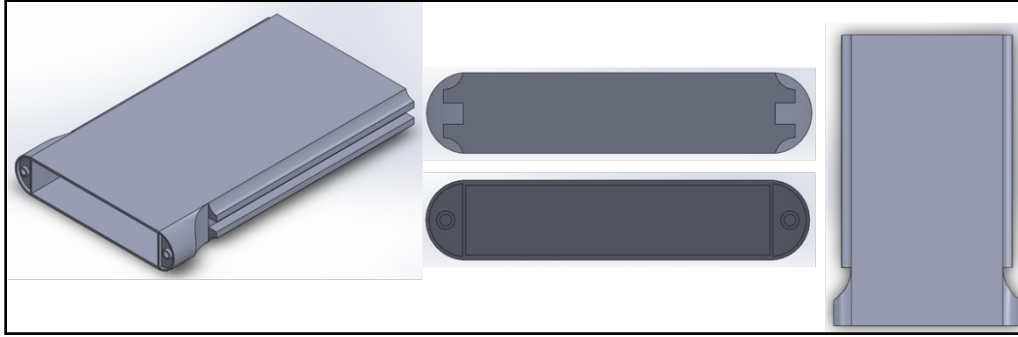


Fig. 7 DS SolidWorks computer-aided design (CAD) illustrations of the cassette case

3.4 Enclosure

Purpose: The enclosure is the case for all of the cassettes, the BA5590 female connector, and the energy harvester circuit. This adds additional mechanical support and other environmental resistance. The iBAT is completely encased in the enclosure.

Material: The material is ABS plastic formed via injection molding or additive manufacturing.

Features: The enclosure has self-locating features to allow the user to slide the quads in one by one. There are four to six 4–40 tapped screw holes for each corner. On the top face walls, there is a trench in-between the screw holes and inner edge. The o-ring is inserted to create a seal. There is 0.5-mm cut-out on the outer edge of the enclosure open face to allow an overhang of the enclosure's cover. The overhang feature creates a more effective water resistant seal. There is a large gap above the quad stack. This spacing is for the insertion of the BA5590 female connector. The BA5590 female connector is mounted on the enclosure's cover. There is cut-out on the enclosure cover for the connector. The back side of the enclosure cover has standoffs and plastic supports to mount the energy harvester board. The cover has 4–40 clearance holes in all 4 comers. Figures 8 and 9 show illustrations of the enclosure and cover.

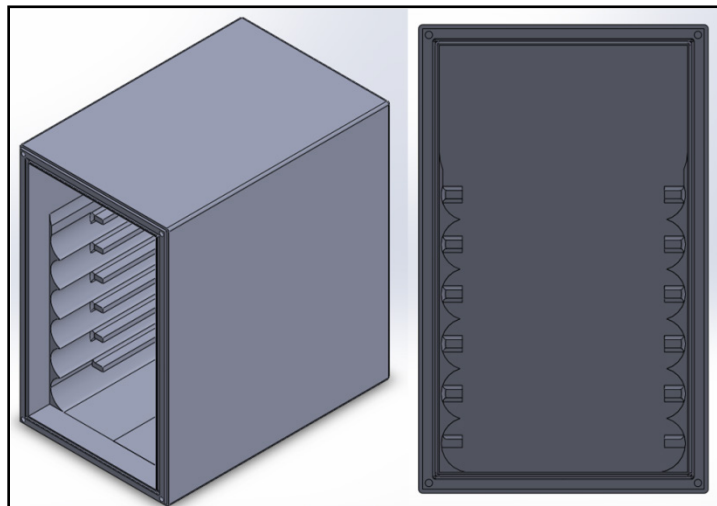


Fig. 8 DS SolidWorks CAD part of the enclosure case

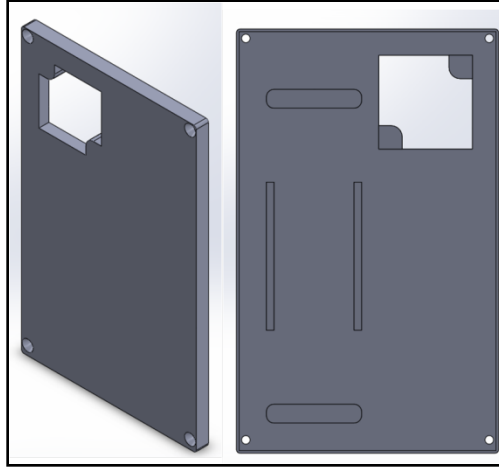


Fig. 9 DS SolidWorks CAD part of the quad case

3.5 Board-to-Board Electrical Connectors

Purpose: Samtec Board-to-Board Electrical Connectors are used to electrically and mechanically connect the components together. Samtec connectors are commercially available, highly reliable, and tiny.

Features: The TMM 2-mm Low Profile Terminal Strip headers are used on the packets and quads. Their pitch is 2 mm and they have a contact system of 0.50 mm square post.⁴ The orientation is vertical, right angle. The termination is through-hole connection. Two headers are placed on the top pin holes of each 6 packet set. The SQT 2 mm FleXYZ™ Cost-effective Tiger Buy™ Square Tail Socket Strip is connected to the right angle headers.⁴ In describing the cassette feature, the 2 leads are protruding out of the case. Their pitch is 2 mm and they have a straight orientation. The SMM 2 mm Tiger Eye™ High Reliability Socket Strip is connected to the energy harvester board. Its pitch is 2 mm and it has a vertical orientation. The termination is a surface mount. There special features include high reliability multi-finger beryllium-copper contact system.⁴ They are mechanically and electrically connected to the SQT leads by being pressed in as the enclosure's cover is screwed in place. The Appendix shows technical drawings and illustrations of the components.

3.6 Cymbet EnerChip Thin-Film Battery

Purpose: This provides onboard backup and energy storage for the COTS iBAT to directly power sensor. The iBAT trickle charges the battery array. By definition, it is an energy harvesting system when coupled with any type of energy transducer.

Features: The thin-film battery is a 50-μAh energy storage with an integrated power manager. It has a temperature-compensated charge control and is rated for 5000 recharge cycles. The output voltage is 3.3 V with a recharge time of 20 min at 80% of energy storage. The package dimensions are 9 x 9 x 1 mm. Figure 10 shows package image and schematic of the Cymbet EnerChip thin-film battery.

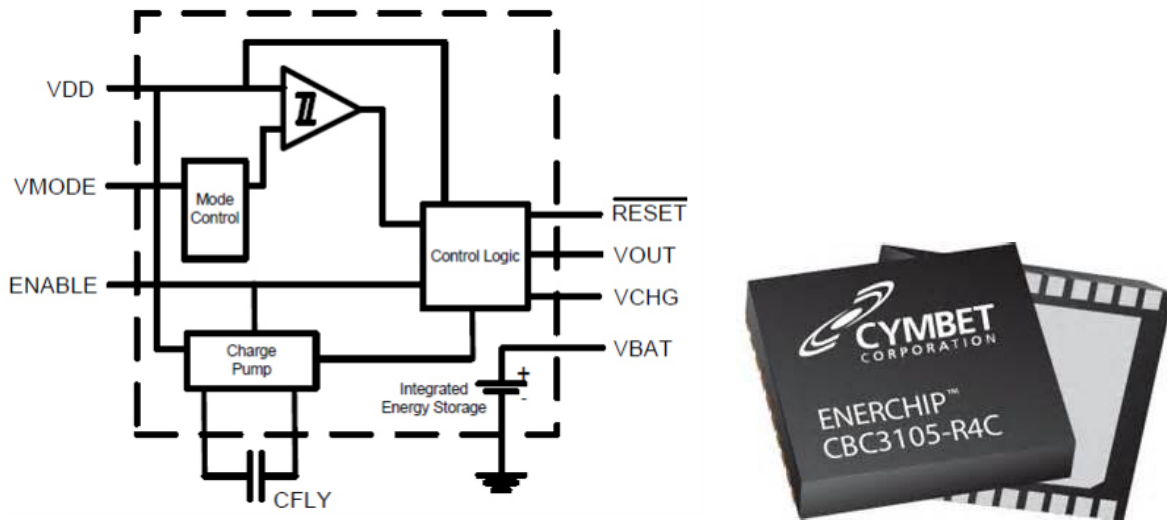


Fig. 10 Cymbet EnerChip thin-film battery schematic (left) and battery package (right)⁵

4. Layered Material Selection

4.1 Optical Adhesive

The energy conversion depends on the photon transmittance from one surface to another (phosphor and solar cell). The ^3H platelets are placed in between solar cells on both sides. Optical epoxy is applied to the interface serving 2 purposes: adhesion and light transmittance/refraction. Norland Optical Epoxy 83H was chosen due to its high refractive index of 1.56 and favorable adhesion to metals, ceramics, and plastics. The epoxy cures under ultraviolet (UV) light with a wavelength between 320 and 380 nm.⁶ It hardens after curing, but does not become completely brittle. The adhesive adds a small amount of resiliency providing strain relief from vibrations or temperature extremes.⁶ Figure 11 shows the spectral transmission of 83H. Table 1 shows the typical physical properties of the optical adhesive.

Spectral Transmission of 83H

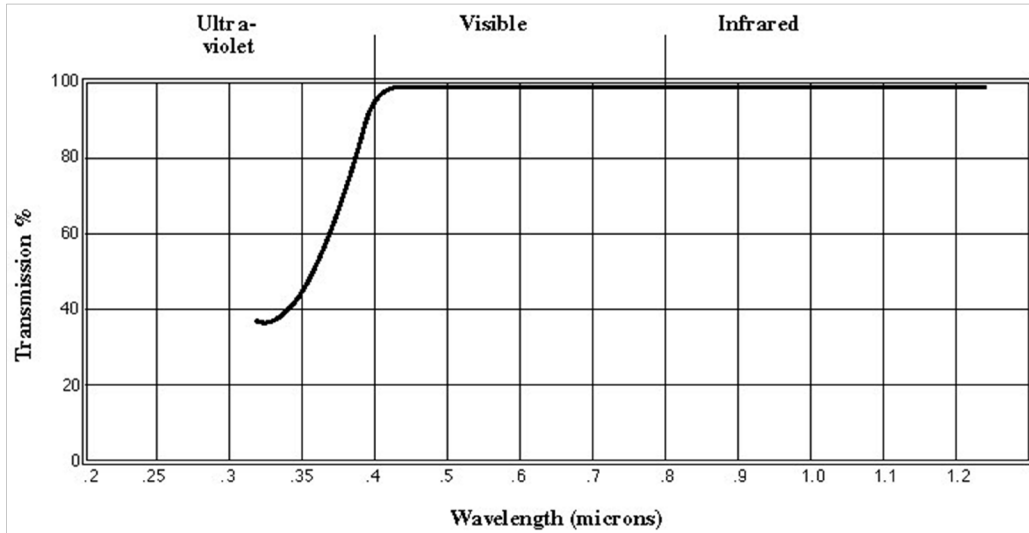


Fig. 11 Spectral transmission of Norland 83H⁶

Table 1 Norland 83H properties⁶

Typical Properties of NOA 83H	
Solids	100%
Viscosity at 25° C	250 cps
Refractive Index of Cured Polymer	1.56
Elongation at Failure	30%
Modulus of Elasticity (psi)	160,000
Tensile Strength (psi)	3,500
Hardness - Shore D	85

4.2 Multilayered Epoxy Encapsulate Using Function Graded Materials

Additional layers of protection are required for protection against platelet and solar cell breakage and to prevent potential ³H contamination for the safety of the users. Two different types of epoxies are used in the iBAT design. Both epoxies are 3M products. The first layer of epoxy is a flexible type called DP190. It is translucent, has a 90-min worklife, and possesses a high shear and peel strength (a hardness of 35 Shore D, which is similar to hard rubber, and a shear strength of 650–1000 psi).⁷ After that layer cures, another epoxy is applied. This is a high impact resistant epoxy called DP420. It is a white, low viscosity liquid that when applied hardens in 20 min. Once cured, it has a 15-80 Shore D hardness and a shear strength of 4500 psi.⁸ The harder outside layer absorbs most of the kinetic energy from an impact while the flexible epoxy allows

deformation during shock. If the material order was reversed, high deformation might break the PVs and platelets. Stress concentration is higher on the harder material compared to applying a load or impact on the softer side. However, the deformation will be higher with the lower Young's modulus material; thus, the higher Young's modulus material should be made out of the outer layer.⁹

4.3 ABS Plastic

The cassette and enclosure are made of ABS plastic. ABS plastic is lightweight; can be injection molded, extruded, or additive manufactured; and has a high impact resistance. This makes it an excellent material for the COTS iBAT. Table 2 displays typical properties of ABS.

Table 2 Mechanical properties of ABS¹⁰

Mechanical Properties	Test Method	American Standard	Metric
Tensile Strength, Type 1, 0.125	ASTM D638	3.2 ksi	22 MPa
Tensile Modulus, Type 1, 0.125	ASTM D638	236 ksi	1,627 MPa
Tensile Elongation, Type 1, 0.125	ASTM D638	6%	6%
Flexural Strength	ASTM D790	6 ksi	41 MPa
Flexural Modulus	ASTM D790	266 ksi	1,834 MPa
IZOD Impact, un-notched	ASTM D256	4 ft-lb/in	106.78 J/a
IZOD Impact, notched	ASTM D256	2 ft-lb/in	213.56 J/a

5. COTS iBAT Assembly

The assembly includes all of the materials listed previously along with additional required tools for handling, safety, and precision. The GaAs solar cells are placed on a vacuum table so they can lay flat. Five cells are soldered in series, which makes up a single layer. Optical adhesive is applied on the PV surface using a tiny paintbrush. Using plastic tweezers, ³H platelets are placed on the surface. After the platelets cover the surface, the layer cures underneath a UV lamp (1.5 inches away from surface) for 40 s. Another solar cell array (5 cells) is placed on top of the ³H layer. Figure 12 shows an image of the 2 layers before they are wired and glued together.

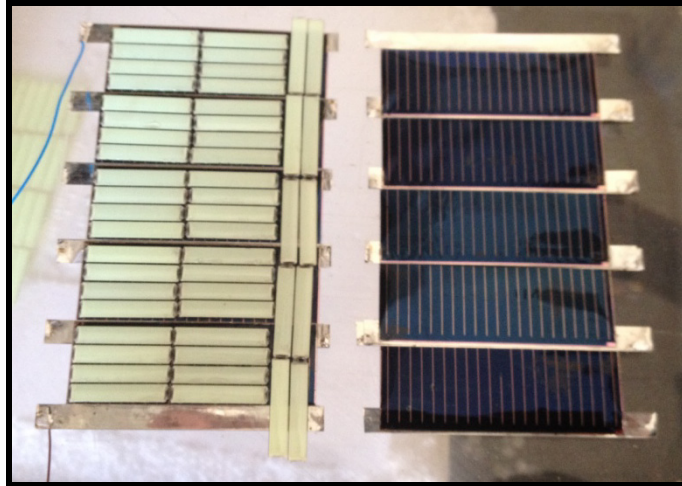


Fig. 12 Image of the GaAs arrays before the layers are wired and glued together making a single sandwich to surround the platelets

The 2 layers are connected in series, which is considered a single sandwich. Optical adhesive is applied to the edges of the PV layers, which physically attaches them together after a 40-s cure. Double-side Kapton tape is placed on the other side of the sandwich. This process is repeated throughout the entire assembly. Each sandwich is attached to each other and connected in parallel. Four sandwiches make up 1 cassette. 3M DP190 adhesive is applied to the entire surface of the cassette (>1 mm in thickness) and allowed to cure. Then a thin layer (<1 mm) of 3M DP420 is applied to surface. After curing, the sandwich is slid into an ABS cassette. Samtec SQT connectors are soldered to plus and minus wire leads. The process is repeated 6–10 more times (6–10 cassettes), depending on the necessary power needed for application. The individual cassettes are inserted into the enclosure starting from the bottom to the top. The BA5590 female connector is secured in to the enclosure cover. The energy harvester circuit board is screwed into the cover stand-offs and platforms. The board includes 10 to 20 Cymbet EnerChips depending on power requirements. Lastly, the cover is aligned and screwed on to the enclosure. The SMM connectors are aligned to the SQT leads protruding out of each cassette, and electrically and mechanically connected with the enclosure's cover being screwed and pressed in place. Figure 13 shows a three-dimensional (3-D) CAD of the COTS iBAT assembly, its components, and the actual cassette.

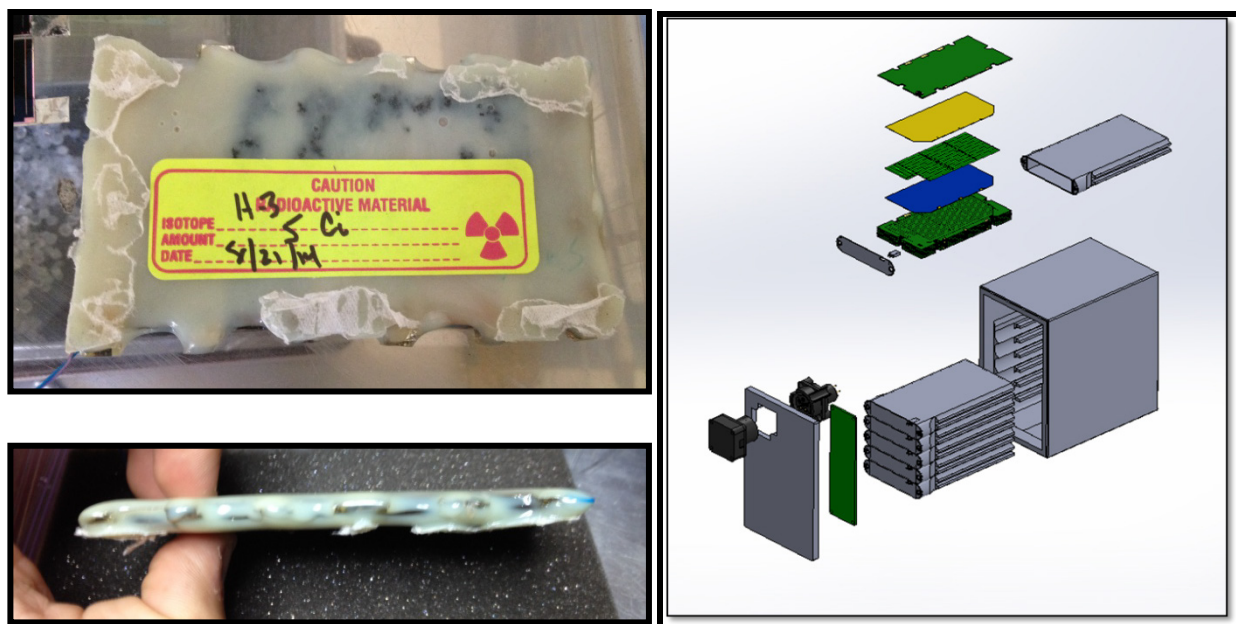


Fig. 13 The iBAT GaAs cassette (left) and the 3-D CAD of the iBAT assembly (right)

6. COTS iBAT Power Management and Application

The power output goal is a total electrical power output of $100 \mu\text{W}_e$ using 100 Ci. This can be achieved with the InGaP solar cells, over the GaAs cells presently used. GaAs PV generates a total of $50 \mu\text{W}_e$ from 100 Ci of ^3H . Each sandwich has an open circuit voltage of 3.5 V and a short circuit current of $0.78 \mu\text{A}$ generating with $2.5 \mu\text{W}_e$. Each cassette has an open circuit voltage of 3.5 V and a short circuit current $3.1 \mu\text{A}$ generating with $10 \mu\text{W}_e$. The total enclosure has an open circuit voltage of 3.5 V and a short circuit current of 15 to $30 \mu\text{A}$ depending power application needs. The Radiation Observations with Communications Sensor (ROC) Generation 3 (G3)¹¹ leverages independently proven technologies recently available in the medical instrumentation field including avalanche photodiodes (APDs) that operate at reduced voltages, low-power wireless network protocols, high efficiency boost converters, and ferroelectric random access memory (FRAM) microcontrollers. Rapid development is possible because much of the ROCG3 is already designed and operational. All of the independent components in ROCG3 are COTS components. This includes the Linear Technology/Texas Instruments core using the Wolverine MSP430 ultra-low power FRAM processor. The Wolverine allows the system to be capable of operation in sleep mode without the need to refresh registers or reload memory from flash RAM. Full-power operation of this system with all systems active is measured at $300 \mu\text{W}_e$, which is potentially a record-setting level of power efficiency for a continuous radiation detection system.

6.1 Radiation Detection

Scintillation measurements give the user the ability to perform spectroscopic assays of unknown radioactive events and sensitive counting in 1 unit. APDs are available from the medical community for sensing radiation for imaging studies of the human body. Unlike other APDs, Athena APDs operate at very low voltages, which allows for a low-power boost converter to power the APD, thus reducing power demands during operation. These photodiodes are ruggedized to meet the demanding weight and durability constraints of military deployment. Typically, these radiation sensors are deployed as detectors operating in Geiger mode. However, radiation detection characterization has been integrated into the radio using a photon pulse-height binning system. The result is the ability to determine the type of radioactive material using spectroscopy techniques based on the binning. Our detectors can discern energies down to 100 keV.

6.2 Processor and Wireless Radio

The selections of wireless standards were originally driven by the need to take advantage of the lowest power and highest range option available. Our first stab at this was with Zigbee. We, also, investigated Bluetooth low energy (BLE) and Wi-Fi. In most cases, sub-gigahertz radios give the lowest power, longest range, with a decent bit-rate for unattended sensor applications.

The core data acquisition system is built around the popular MSP430 processor core from Texas Instruments. This system allows for deep levels of sleep to reduce the power consumption of the processor. The system is also designed by the US Army Research Laboratory (ARL) to take advantage of variable processor voltage operation. This interesting approach to power management reduces full-power consumption by limiting operating voltage when peripherals are not needed by the MSP430. The wireless radio operates at 915 MHz and offers variable power levels to aid in transmitting long distances (1 mile line of sight) and short distances for high bit-rate bursts. Sleep modes for the radio can be controlled by the MSP430. Figure 14 shows the major components of the low-power radiation sensor: radio, global positioning system (GPS), and ultra-low power data processor.

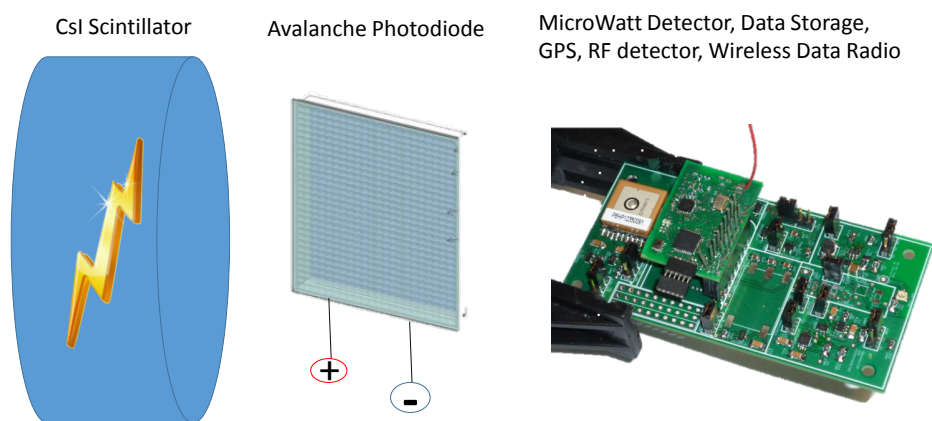


Fig. 14 Major components of ROCG3, with ultra-low power data processor, radio, and GPS

Each ROCG3 can be operated for such a long period of time that normal batteries would not be appropriate for their self-discharge characteristics. For example, a typical smartphone rechargeable battery would power the system for 15,500 h continuously, but the self-discharge of the battery would render it dead in a fraction of that time.

Table 3 displays the power budget predictions of the IDEC iBAT. The iBAT electrical output totals to $100 \mu W_e$, which means it delivers 8.64 J/day for more than a decade. It has the capability to power an ultra-low power sensor (communications node, radiation sensor, and camera sensor) designed and built as examples by the Alternative Energy Team. All 3 low-power devices have 3 similar modes: hibernate/sleep mode, measure, and data transmission. All 3 units awake from sleep mode due to an event (motion, vibration, EM, or radiation) triggered by a passive or nanowatt powered sensor such as a piezoelectric transducer, antenna, or scintillator illumination from an incoming high energy photon of a radioactive material. Sensor hibernation increases battery lifetime and allows the entire system to be more energy efficient. The sensor and battery system can last more than a decade in a remote and harsh environment due the sleep mode implementation of the sensors and the mechanical and temperature robustness of the battery. The camera unit can support up to 3 images daily. The radiation sensor can operate for 10 min per day or 20 individual 30-s detection periods. The communication mode can operate for 2.4 min per day.

Table 3 Capability chart for isotope power source and prospective sensors

Isotope Battery Power Budget Predictions						
Power	100	μ W				
Energy	8.64	J/day				
Communications Node			Transmit	Standby	Hibernate	Total Joules
TI 3200 Processor/Wi-Fi Radio	W		6.60E-3	6.60E-4	3.96E-08	
OPERATING TIME	h		0.1	2.63	20	
ENERGY USED	J		2.38	6.25	2.85	8.63
Radiation Sensor			Transmit	Measure	Hibernate	Total Joules
ROC GEN3	W		1.02E-02	8.91E-04	0	
OPERATING TIME	h		0.024	2.4	0	
ENERGY USED	J		8.84E-01	7.70	0	8.58
Camera Sensor			Transmit	Picture	Hibernate	Total Joules
CAMERA SENSOR	W		6.60E-03	2.31E-01	3.96E-08	
OPERATING TIME	h		0.024	0.0097	24	
ENERGY USED	J		5.70E-01	8.07	3.42E-03	8.64

6.3 Batteries

Recent advances in LiSoCl₂ primary batteries allow for portable energy storage with 2 times the energy density of existing primary lithium batteries. Table 4 displays the battery specifications of ROCG3 battery pack.

Table 4 Battery specifications of ROCG3 battery pack

Specification	ROCG3 Isotope Battery Pack (10-year lifetime)
Capacity	10 J/day
Weight	30 g
V _{oc}	3.5 V
Dimensions	25.6 mm x 48.4 mm
Operating temperature range	-20 to 93 °C
Shelf life	4% / year (H ³ half-life)

7. Conclusion

A 100- μ W_e iBAT replicating the design and size of a BA5590 Army battery was accomplished. The battery's design is simple and feasible for the US Army. The features of the battery fulfill the Design for Assembly guidelines.¹² The self-identifying/locating features allow the battery to be easily assembled. The components are commercially available products. The materials used in the battery provide protection from mechanical shock and the environment (sand, dirt, water, etc.).

8. References and Notes

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Appendix. Packet Design

Figures A-1, A-2, and A-3 show the commercial specification for the mini-connectors used to connect the multiple sandwiches together within the packets.

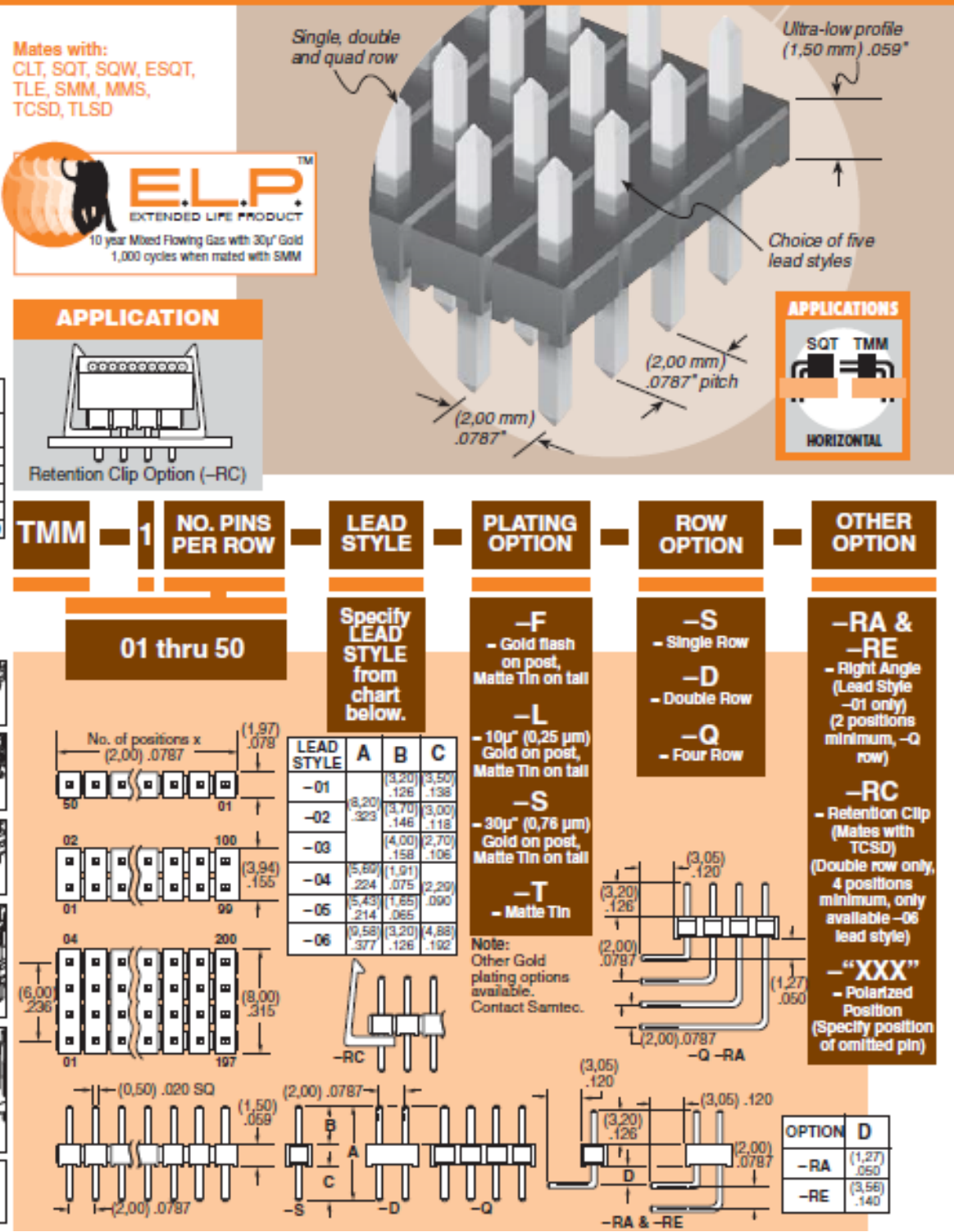


Fig. A-1 TMM Board-to-Board Electrical Connectors (image courtesy of <http://www.samtec.com/technical-specifications/Default.aspx?SeriesMaster=TMM>)

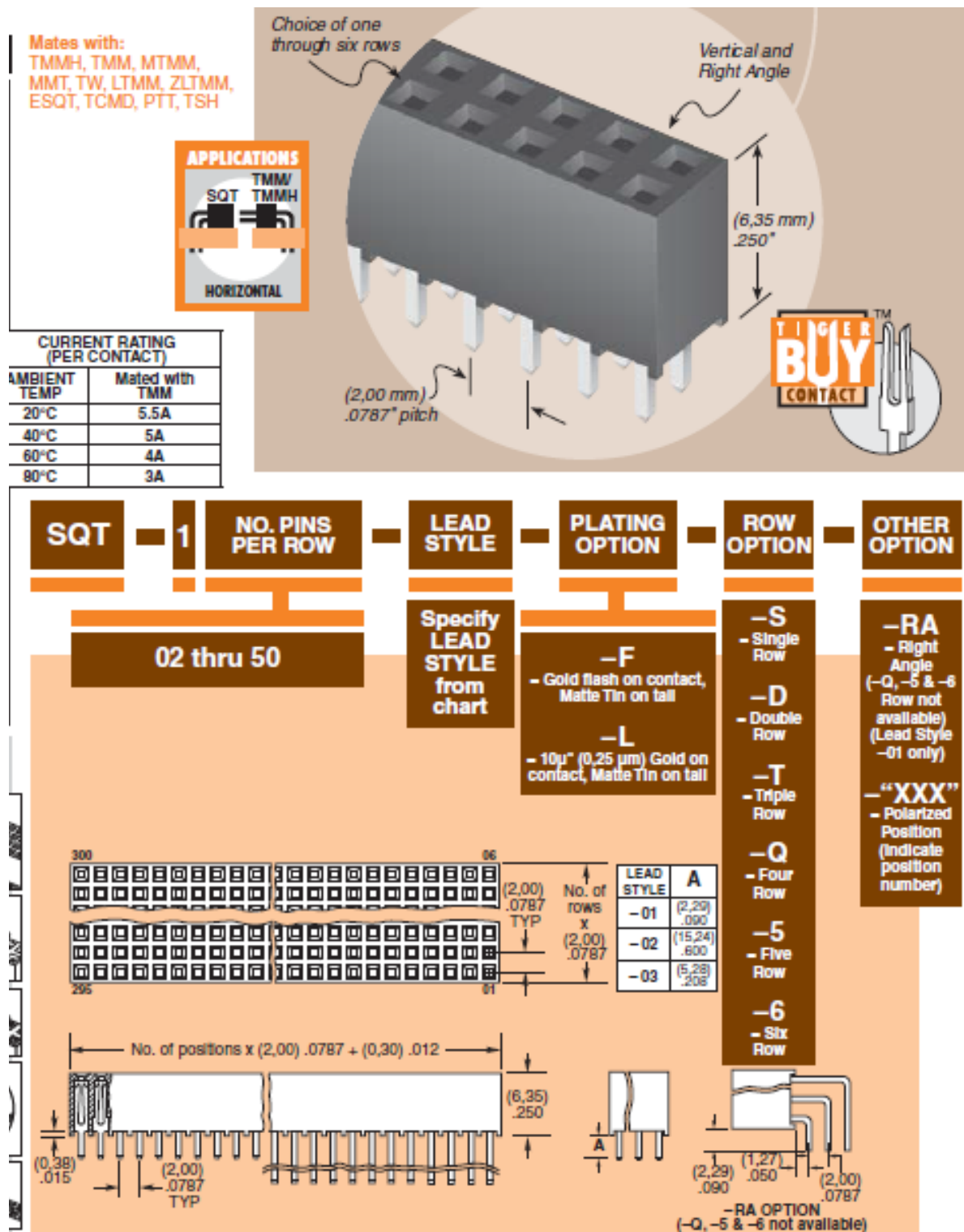


Fig. A-2 SQT Board-to-Board Electrical Connectors (image courtesy of <http://www.samtec.com/technical-specifications/Default.aspx?SeriesMaster=SQT>)

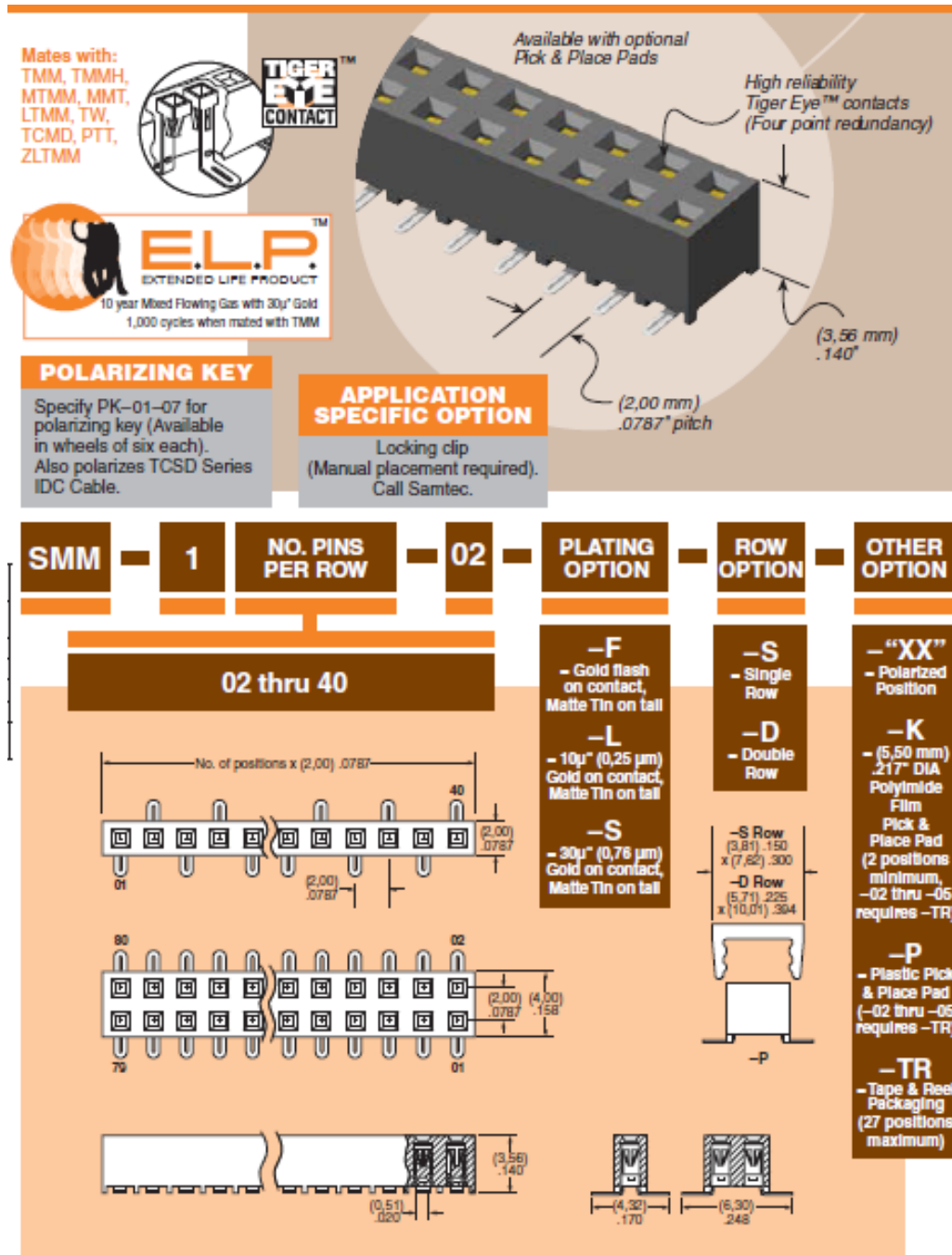


Fig. A-3 SMM Board-to-Board Electrical Connectors (image courtesy of <http://www.samtec.com/technical-specifications/Default.aspx?SeriesMaster=SMM>)

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
APDs	avalanche photodiodes
ARL	US Army Research Laboratory
a-Si or a:Si	amorphous Si
BLE	Bluetooth low energy
CAD	computer-aided design
COTS	commercial-off-the-shelf
DC	direct current
EM	electromagnetic
FRAM	ferroelectric random access memory
G3	Generation 3
GaAs	gallium arsenide
GPS	global positioning system
^3H	tritium
iBAT	isotope batteries
InGaP	indium gallium phosphide
LiSoCl ₂	lithium thionyl chloride
PV	photovoltaic
ROC	Radiation Observations with Communications Sensor
Si	silicon
UV	ultraviolet
ZnS	zinc selenide

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